Characterisation of a Silicon Photomultiplier of 64 channels

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Abstract: This work presents the study of a 64 channel silicon photomultiplier (3.2 x 3.2 mm^2 each channel) built by Hammamatsu. From the experimental data, the values of the gain at four different voltages (68V, 68.5V, 69V, 69.5V) are measured for each channel and, the breakdown voltage and the gain per voltage, for each channel, have been determined. Also measurements at 70V have been preformed but rejected because of the amount of noise.

I. INTRODUCTION

The purpose of light detectors is to convert electromagnetic radiation (photons) into an electronic signal to make the readout possible.
In this study the detector is a solid state silicon photomultiplier (SiPM) of 64 channels. The fact that 64 channels of 3.2 x 3.2 mm^2 instead of 1 channel of 25.8 x 25.8 mm^2 are being used is due to two main reasons:

- The time of response increases proportionally with the area, i. e. the smaller the area, the faster the response.
- Dividing the active area in 64 channels improves the spatial resolution of the detector.

When a photon that goes through a silicon detector is absorbed, it causes the promotion of an electron from the valence band to the conduction band, thus creating an electron-hole pair. When a voltage is applied, because of the electric field inside the depletion region, these charge carriers are accelerated, therefore a flow current is detected in the anode (holes) and in the cathode (electrons).
Each of the 64 channels of the SiPM consists on an array of 3600 avalanche photodiodes (APDs) of 50 x 50 μm^2, connected in parallel working in Geiger mode. Under these conditions the output of the APD is binary, where the response is the same regardles of the number of photon. However the signal of a SiPM is proportional, within a certain range, to the number of APDs which are activated, hence it is proportional to the number of photons detected, and thus it can measure light intensity.

II. THEORETICAL FRAMEWORK

A. PN junction

Pure silicon is in equilibrium (neglecting local fluctuations) of electrons and holes. This means that there is no electric field inside it, this state is called as intrinsic. It is possible to dope pure silicon by adding impurities.
If it is N type, the dopants are electron donors, atoms that have five electrons in their external shell, thus there is an excess of electrons (the majority charge carrier is negative).
If there is an excess of holes (positive charge carrier), the silicon is P type, the dopants are electron acceptors, atoms that have three electrons in their external shell.
When the P region and the N region are joined, a PN junction is formed. Due to the gradient of charge carriers between the two regions, a diffusion current of holes from the P side to the N side, and one of electrons from the N region to the P region appear, inducing a charge density distribution (positive at the N region and negative at the P region).
The minority charge carriers which diffuse recombine with the majority charge carriers of each region. This charge carriers redistribution only affects a region close to the junction and its called depletion region. The silicon remains mainly neutral, but because of the charge density distribution in the depletion zone an electric field appears, which creates a drift current that contraposes the diffusion current until an equilibrium state is reached. The drift electric field in equilibrium is associated to an electrostatic potential that modifies the charge carriers' energy. It is the responsible for bending the energy bands inside the depletion region. However the total current inside the silicon is zero.
Also the junction can be subjected to the application of an external electric field, which changes its depletion region, its energy bands and its behaviour. The polarization can be direct or reverse.
If the polarization is reverse, the barrier increases due to the external field that is in the same direction of the electric field inside the depletion region. Also there is a new disequilibrium between the two currents that exists inside the silicon, it creates a negative current (transport of electrons towards N region, and holes towards P region), as we can see in figure 1.

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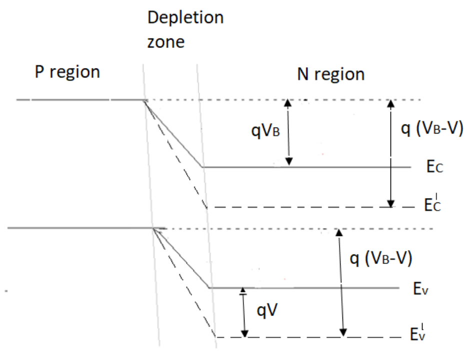

FIG. 1: Bands curvature of PN junction without polarization (solid line) and with reverse polarization (dashed line).

B. Avalanche Photodiode (APD)

An APD is a PN junction that works at high reverse bias voltage exceeding breakdown voltage (Geiger mode).
If the electric field inside the depletion region is high enough, the charge carriers are accelerated and their kinetic energy increases. By hitting the crystal lattice, electron-hole pairs are created due to the impact ionization, so an avalanche is produced, Geiger discharge.
The avalanche effect results in an amplification of the signal by a given multiplication factor, called gain. The avalanche produced in the APD must be turned off or stopped to be able to measure a new event, so a quenching mechanism is used. It reduces the bias voltage below the breakdown point so the device can recharge back and be available to detect new events. The avalanche multiplication depends on the mean free path of electrons between ionizing collisions which depends on the temperature, thus the gain varies also with temperature.
In an APD working in Geiger mode the gain is defined as the number of carriers created during an avalanche discharge, so we can express it as

$$G = \frac{Q}{q_e} = \frac{(C_D + C_Q)\Delta V}{q_e} \tag{1}$$

Where ΔV is defined as the excess bias voltage ($V_{Bias} - V_{Breakdown}$), C_D is diode capacitance, C_Q is the quenching capacitance, and q_e is the electron charge.

C. Silicon PhotoMultiplier (SiPM)

A SiPM or multi-pixel photon counter (MPPC) is a matrix of pixels working in Geiger mode, under bias voltage over the breakdown voltage and connected in parallel. A single pixel has the structure of an APD showed in figure 2.

Above a p^+ substrate, a p^- type layer is found. The depletion region, where the electric field is high enough for working in Geiger mode, embraces the region between p^+ and n^+ layers. Also there are n^- guard rings, whose job is to ensure the uniformity of the electric field and discard surface and leakage currents.

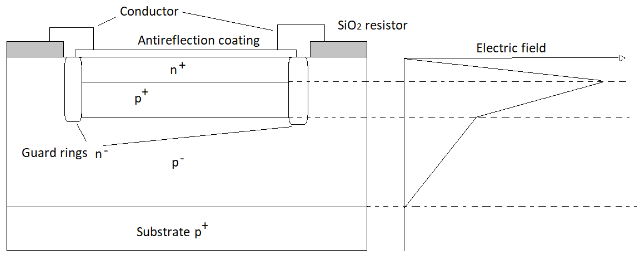

FIG. 2: Representation of the structure of an APD and the shape of the electric field inside it.

Since all avalanche photodiodes also referred to microcells are working in parallel, the final signal is the sum of all the signals of each pixel. So even though each microcell has a binary response, the signal of a SiPM is proportional to the light that arrives through each pixel. Consequently it can measure not only if there is light, but also its intensity, so it is possible to measure the number of photons that arrive to the SiPM.

III. EXPERIMENTAL PROCESS

A. Setup

The S12642-0808 silicon photomulitplier detector manufactured by Hammamatsu is formed by 64 channels of 3.2 x 3.2 mm^2. Each channel with an effective photosensitive area of 3 x 3 mm^2 with 3600 microcells. The whole detector is about 25.8 x 25.8 mm^2 and its structure is represented in figure 3.

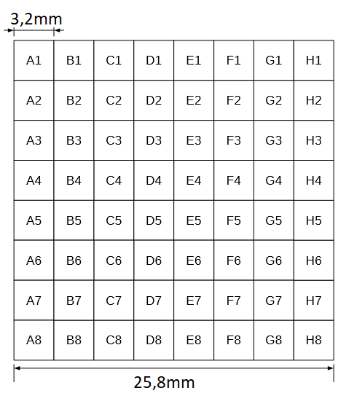

FIG. 3: Schematic representation of the SiPM used.

To characterize a SiPM and study its gain, we have to measure the charge created by the detector when it is being irradiated with photons, thus an electromagnetic radiation source is needed. In this study the chosen source is a red laser owing to its penetration length, about 3μm, which allows the creation of an electron-hole pair near the surface.
As this detector is being characterized to be a single-photon detector, an attenuator is used to decrease the intensity of the laser. The diameter of the laser beam is smaller than the total SiPM's area. Instead of irradiating only a few channels, we are interested in lighting homogeneously the 64 channels, that is why a diffuser is used as we can see in figure 4.
To control the environment around the sample, all the measurements have been done inside a blackbox, where it is also possible to maintain the temperature at a constant value. We know that the gain depends on the temperature which has been fixed at 18°C.
The readout of the 64 channels of the silicon photomultiplier has been carried out by an ASIC named MUSIC M05 to amplify the signal from the SiPM, developed by the technical group at ICC at University of Barcelona, plus a WaveCatcher that allows to read 8 channels simultaneously.

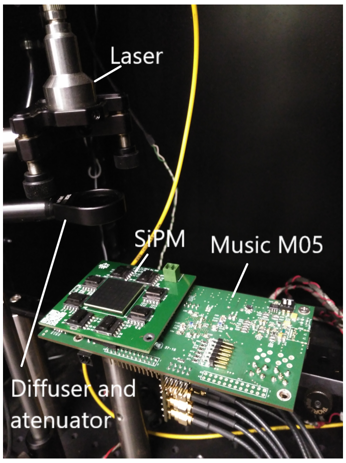

FIG. 4: Experimental Setup used.

B. Data analysis for one channel

As mentioned in the theoretical framework, a reverse bias is applied on the sample to work as a detector, this bias has to be higher than the breakdown voltage.
In this study the gain was measured at different voltages and certain results were derived from these measurements.
When the laser is illuminating the surface of the SiPM, at some point one or more photons arrive to the surface of the channel under study, channel 'A1' in this case (figure 5), and they create an electrical signal.
The waveform produced is saved in a file, where 3000 events are stored. In this file there is information about the shape of this waveform, its height and its width, and about the pedestal range (noise). Only one waveform per event is saved.

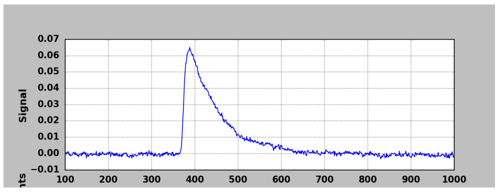

FIG. 5: Waveform for one of the events detected in channel A1 at 68.0 V.

Since the data acquisition is synchronized with the laser, a pedestal and a signal region can be defined. The average charge in the pedestal area (from 100 to 350, by looking the x axis, which is related with the time, on figure 5) is subtracted to the charge in the signal area (from 350 to 550) to determine the total charge for each event.
The data were also analyzed by defining the signal area between 350 and 600 and no significantly changes were noticed.
By integrating the area below the waveform it is possible to compute the total amount of charge generated by the event. A higher amplitude implies higher intensity and this means that more photons have arrived to the channel, so more charge was generated.
It is possible to produce a histogram to check how the events are distributed, thus to plot the charge distribution of the channel.

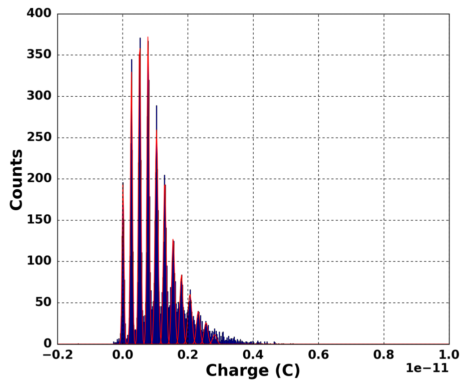

FIG. 6: Fitted histogram for channel A1 at 68.0V,with the number of counts as a function of the charge detected (Coulomb).

The distribution presents some peaks (figure 6) which correspond to the different type of events, with 0,1,2... photons detected. Each peak was fitted with a gaussian. If we compute the position of the center of the gaussian of every fitted peak, we know the amount of charge created for a given number of photons.

Once this has been computed, we plot the data (figure 7) and we can see an ascendant linear regression, where the slope of the line gives us the value of the gain for channel 'A1' and at a certain voltage.

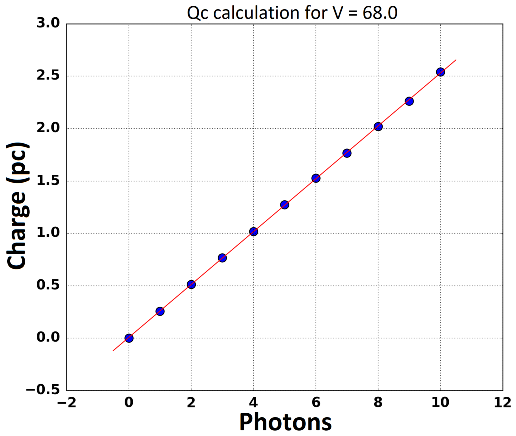

FIG. 7: Representation of the charge (pC) as a function of the number of photons of the channel A1 at 68.0 V.

In figure 8 we can see the value of the gain as a function of the applied voltage. As it is linear, it can be fitted by a linear regression. Its slope is the gain per voltage unit and its independent term is related to the breakdown voltage (value of the abscissa when the ordinate is zero).

After analyzing a single channel, the data analyses programs have been updated to automate the execution and thus the analysis of the 64 sets of measurements for each voltage.

C. Results and conclusions

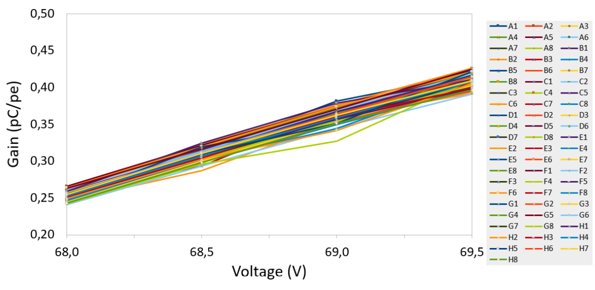

FIG. 8: Representation of the gain (pC/pe) dependence with voltage (V) for the 64 channels.

First of all, we can see in figure 8 that we can prove our first hypothesis, the gain depends on the bias voltage and it increases linearly as applied voltage increases, this is easily explained considering the energy of the particles. When electron-hole pairs are created inside the detector their energy depends on the applied voltage. The higher the bias, the higher the ionization energy. Thus, more electrons can be extracted, so the signal is larger. As a result, the gain is higher, as described by equation 1.

In figure 8, the values of the gain for the 64 channels at 68, 68.5, 69 and 69.5 V are presented. The values for 70V were not used in the end because there is so much noise that is hard to distinguish the signal for each event type (0,1,2,... photons).

Our interest is the maximum homogeneity of gain in the sensor. If it is not homogeneous, the analysis of the data will be more complex. For example, if the gain of one channel is significantly higher than the others when the same amount of light reaches both channels, the readout will be different. That is why a 2D color map representing the value of gain/voltage is plotted (figure 9), where each box corresponds to one channel (same structure than in figure 3) and the colour shows the number of particles created, thus the gain per voltage, which has a value of 650000 electrons created per photon and Volt.

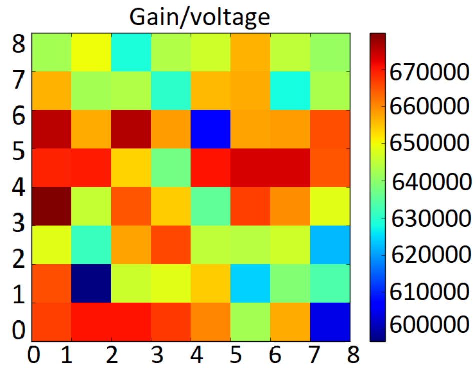

FIG. 9: 2D color map representation of gain per voltage in number of particles created, following the same structure as in figure 3.

The same values were plotted in a 3D histogram (figure 10) where each column represents one channel (its structure is the same as in figure 3). All the values have been normalized, where the maximum is set to one. A maximal dispersion of 10% is observed. This level of homogeneity could be enough depending on the experiment or study that one wants to perform.

By representing the breakdown voltage for each channel in a 2D map (figure 11), where each channel is located as in figure 3, it is possible to see that their values are around -65.5 V. This is the value we expect according to the manufacturer.

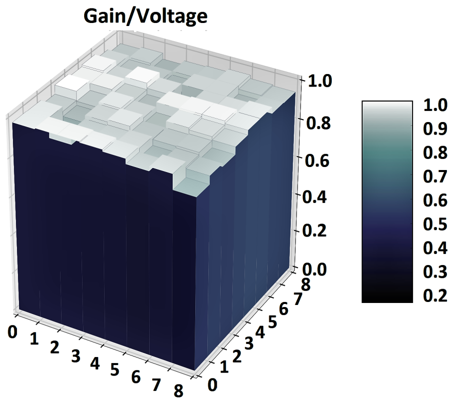

FIG. 10: 3D normalized histogram of gain per voltage, following the same structure as in figure 3.

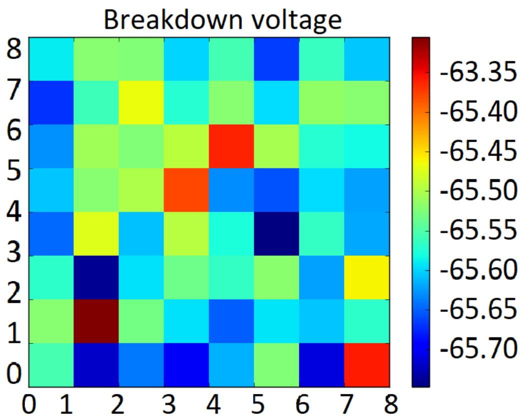

FIG. 11: 2D color map representation of breakdown voltage in Volts, following the same structure as in figure 3.

By representing them in a 3D histogram (figure 12) where each column represents one channel, we can see that the dispersion is below 1% So we can say that this device is highly homogeneous in breakdown voltage.

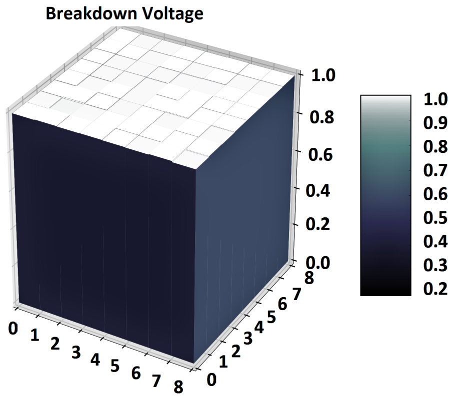

FIG. 12: 3D normalized histogram of breakdown voltage following the same structure as in figure 3.

On the basis of a measuring setup and some basic data analyses programs (for one channel SiPM), the setup has been implemented and used to automatize the data acquisition and the further analysis of the 64 channels. Furthermore, the results that we have obtained are satisfactory according to the manufacturer data.

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